The Physical Bases of Perception

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The principles of physical science can define limits to the stimuli that can influence biological organisms and, for a particular organism and sensory structure, can give information about sensitivity and information-carrying capacity. When these ideas are applied to human sensory systems, in particular to hearing and vision, it is found that the major problem is not one of sensitivity but rather that of coping with the immense amount of sensory data provided by the ear or eye.

Perception is, almost by definition, a process that takes place at a neurophysiological or even psychological level. Before these levels are reached, however, there must be some interaction between the outside world and the perceiving organism to provide, in a sense, the raw materials upon which the perceptual process can operate. This part of the perceptual chain lies within the domain of physics and can therefore be the subject of a rather different and much more quantitative analysis than is appropriate at higher levels. Consideration of physical processes can define the limits of what is possible in perception, and can thus provide a set of benchmarks against which the performance of actual systems can be judged; at the same time it can suggest possible mechanisms by which biological perception systems might operate, and strategies for the construction of mechanical perception systems or of aids to human perception.

The physical constraints to perception are twofold. In the first place there must be some mechanism – mechanical, electrical, chemical or whatever – by which the environment can influence the state of the perceiving system, and in the second place there must be some means by which the system can sort out the meaningful part of the received stimulus – the signal – from the background of other meaningless, or at least irrelevant, stimuli – the noise. These same problems exist in the same form if the organism is seeking objective information about itself – the position or stress in a limb, for example – but we should agree to omit discussion of subjective or introspective perception – questions like 'Do I feel happy?' – as being outside the domain of perception with which we are concerned here.

To limit the scope of our discourse further, let us agree that we are concerned primarily with human perception rather than with perception by other biological organisms or by machines, though we shall make a few references to these other cases to point up the powers or limitations of those senses that we ourselves possess.

DETECTABLE STIMULI

It is reasonably easy to make a catalogue of detectable stimuli and to rule out certain other physically measurable entities as being undetectable by the unaided human system, but it is impossible to be sure that our catalogue is complete.

The simplest form of stimulus is chemical, and is exemplified by our senses of taste and smell. It involves physical transport of the stimulating molecules from their source to an appropriate chemical receptor site on the organism, and it is easy to see that such receptor sites could be designed to respond in a particular electrochemical fashion to physical contact with a particular molecule or a class of molecules containing some particular chemical group. We return to the matter of chemical selectivity later, but it is obvious that useful chemical receptors must be at least selective enough that they are not triggered by ubiquitous molecules like nitrogen or oxygen.

If matter itself, with its associated chemical energy, is not to be transferred from source to detector, then at least energy must be transferred, and the simplest form of energy is mechanical energy. All that is required is a coupling device and a deformable detector cell in which mechanical energy is transformed into the electrochemical energy characteristic of nerve signals. The two most familiar human mechanical senses are touch, in which the external force acts nearly directly on the sense cells, and hearing, in which pressure fluctuations travelling through the air are coupled through a thin membrane in the ear and detected by deformable cells in the cochlea.

It is possible, however, to detect the direction and strength of gravity through its distorting effect on deformable tissue, such as a liquid in a tube, in the body. Acceleration produces effects indistinguishable from gravity, as is true in both Newtonian and relativistic mechanics, so that aircraft pilots deprived of instruments rapidly become disoriented in cloud.

Similar deformable detectors give information about bodily configuration and muscular stress. There is no physical reason why biological sensors for quasi-static atmospheric pressure should not have developed, and such a sensor might have given a direct indication of change of altitude, with additional warning of approaching thunderstorms or cyclonic depressions. Presumably the evolutionary value of such a sensor was inadequate.

More subtle in signal capabilities are the influences of electromagnetic radiation, of which the frequency range characterised by light waves is perceptually the most important. The reason for this evolutionary importance is, of course, that this is the range into which is concentrated most of the Sun's energy. Electromagnetic radiation of higher frequency, such as ultraviolet and X-radiation, destroys biological molecules, so is not a good candidate as a vehicle for perception, even if its natural intensity were adequate; on the other hand, waves of lower frequency, infrared and radio waves, suffer from internal detector noise problems unless coherent artificial sources like radio transmitters are available.

Static electric fields are unlikely to be detectable by biological systems, even though they are common features of the environment – the fair-weather electric field near the Earth's surface is about 300 volts per metre and this increases very greatly during thunderstorms. The reason is that the body's fluids are moderately good electrical conductors, so that fields from high-impedance sources are simply cancelled out by induced surface charges. Of course, if the source of the field is of low impedance, as in a piece of electrical machinery, then a clearly perceptible and even painful shock is felt if the field strength or the applied voltage is high enough.

Static magnetic fields can, however, penetrate the body and might in principle be detectable, as in some bacteria, by special cells containing magnetic particles whose function is to convert magnetic field strength to mechanical force, or rather torque. It is not known for certain whether such cells exist in the human body. Another detection possibility arises, however, as soon as motion is permitted, for an electrical conductor such as a cell moving in a static magnetic field generates an electrical potential difference which could in principle be converted directly into a nerve impulse. The detectability of magnetic fields by humans is thus possible but not yet clearly established. It certainly does not seem to be a well-developed sense.

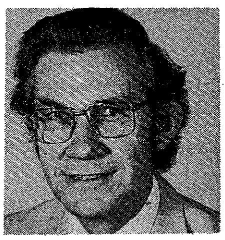
Another type of vehicle for perception might in principle derive from the elementary particles generated by nuclear processes. These stream in copious numbers from the Sun, protons and neutrinos, as well as originating in radioactive decay, alpha and beta particles, and in accelerators and reactors, neutrons, mesons and others. Neutrinos pass through the Earth with little chance of collision, so the possibility of their perception is essentially zero. Other particles in adequate numbers might cause enough collisions to be perceptible, probably as flashes of light, but the incidental damage to other parts of the body would be severe because of their generally high energy. No biological organism appears to have developed specific receptors for detection of such particles, for natural radioactive materials are neither a source of nourishment nor a significant hazard to life.

The only generalised perceptual quantity not covered by this discussion is temperature, and here what is sensed is a state of the external layers of the skin brought about by addition or abstraction of heat energy by radiation or by direct conduction–convection mechanisms. Since the rates of electrochemical processes depend strongly on temperature, this is clearly a detectable attribute of the environment or of the organism itself, though the actual mediating mechanism is either radiant or mechanical at the molecular level. The fact that the skin is moist means that the quantity sensed depends in a rather complex way on air temperature, humidity, air motion and incident radiation.

Finally, as good scientists, we should admit the possibility of perception through the medium of other agencies that have so far eluded the probings of scientific study. No one would be more delighted than the community of physical scientists if, for example, telepathic communication could be demonstrated in an unambiguous way. Physical theory has, for the present, nothing to say on the matter, except that there is nothing in our present knowledge that suggests that such phenomena might be possible. Unfortunately, perhaps, there seems to be no reliable evidence to encourage the view that our list of perception mechanisms is incomplete.

SIGNAL AND NOISE IN HEARING

The perceptual faculties of organisms have developed to serve a wide range of functions – control and



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protection of the animal itself, location of food, evasion of predators and finding of sexual partners of the same species. In each case, the physical problem consists essentially of detecting an appropriately coded signal in the presence of noise. The signal coding may be either genetically determined, like the frequency and modulation of insect mating calls, or else learnt, like the shape, sound or smell of a new type of food or predator. The noise may arise in the external environment as the whole host of irrelevant patterned or random signals generated by other sources. Alternatively, it may be the internal noise in the detection organ itself, generated by the motion of bodily fluids necessary to sustain the sensory cells or even ultimately by thermal fluctuations at a molecular level.

The basic theoretical understanding of the possibilities inherent in such systems of coding, transmission and decoding of information in the presence of noise was derived many years ago in the classic work of Shannon.[1,2] I shall not attempt here to go into any detail but simply state the general conclusions in a qualitative way. The actual theory is, however, a quantitative one. The basic result is that, if a communication channel has available to it a bandwidth W (in hertz or cycles per second) and if the received signal has a power P and is accompanied by random noise with power N (both in watts), then the rate R at which error-free information can be received, measured in bits (*yes–no* decisions) per second, is always less than

$$R_0 = W \log_2 \left(1 + \frac{P}{N}\right) \tag{1}$$

where the logarithm is taken to the base 2. In order to achieve this error-free transmission rate, however, it is necessary to use a sophisticated system for coding and decoding the messages, and this necessarily involves considerable time delays. Practical coding schemes are always simpler than this ideal and achieve information transfer rates R significantly less than R_0 while also allowing a few errors and ambiguities.

The direct application of this result is more obvious in the case of hearing than for the other senses, but we shall see that there is a reasonable correspondence between the qualitative aspects of the situation for each case. Depending upon the nature of the biological organism and its complexity, we also find that a variety of evolutionary strategies has evolved for dealing with the perception problem.

For an animal with a simple nervous system, it is not unusual for the hearing sense to be used simply to detect and locate another animal of the same species emitting the appropriate mating call. Ultimately, some intensity information is needed for location, but initially the system has simply to pass one *yes–no* bit of information in answer to the question, 'Is there a male of my species within range?' It might reasonably take the animal 1 second to act on this information so a rate R of 1 bit per second is adequate. The animal wins in the evolutionary game if it can detect a mate over a large range, or equivalently for a small received signal power P.

From Equation (1), since in many situations the noise power N is proportional to the bandwidth W, the rate R_0 is nearly independent of bandwidth in the limit in which the signal is much weaker than the noise. This is true, however, only if an efficient coding scheme is used that makes use of all the available bandwidth.

The evolutionary strategy of simple animals, such as insects, is to use a very narrow bandwidth and a simple code, so that an insect song is much like a series of repeated dots in Morse code, sent on a note of fixed pitch. The auditory system is sharply tuned to the pitch of the song of the species, and the repetition rate of the dots serves as an identifying code. Clearly this system is simple, and efficient in the design features of the sound generator and the sound receiver; it makes limited demands on the neural processing system. If, however, the available signal power is large, this is not an efficient way to send information at a high rate, as follows from the form of (1) and is intuitively obvious from analogy with Morse code.

In evolution, of course, sound production and hearing are complementary, and it is a fascinating study to see how each communication system in nature has developed to make the best set of compromises between physical size, efficiency of sound production, frequency of operation, atmospheric attenuation, ease of location and so on. Such a discussion is, however, too far from our present subject.

The alternative strategy used by higher animals, including man, is to have vocal and auditory systems of relatively wide bandwidth which then allow, when the signal power is adequate, the transfer of information at a very high rate. Of course, the decoding of this information requires a sophisticated neural processor, the system beginning in the cochlea and ending with the brain, but its information-gathering power is immense.

Human hearing is understandably well matched to human speech, with the formants that distinguish the vowels lying across the spectral region of greatest sensitivity and the consonants spreading across the whole range. The response of the ear is also limited at low frequencies where internal bodily noise and vibration becomes severe.

The intensity range covered by human hearing, between the weakest detectable sound and the loudest sound that does not cause unbearable distortion and discomfort is immense – about 120 decibels, or a factor of 10^{12} in energy. Comfortably understandable human speech lies, not unnaturally, near the middle of this logarithmic range at about 60 to 70 decibels above the threshold. The ear takes a short time to recover from moderately loud sounds and a much longer time, of the orders of hours, to recover nearly fully from prolonged loud noise; however, much of the range is available nearly continuously.

Analysis of sound by the human brain presents many problems, only some of which are governed by straightforward physical laws. Among these however, is the trade-off between analysis in the time domain and that in the frequency or pitch domain. These are complementary variables in the sense that frequency can be determined with an accuracy Δf hertz only in a time Δt greater than $1/\Delta f$ seconds. The fundamental integrating time Δt for the human auditory system seems to be about 50 milliseconds, so that sound pulses closer together than this fuse to produce a single impression. This is probably a property set by the neural processor rather than anything in the ear. The brain can, in fact, adjust its integrating time to a much longer value, about one second, and make frequency discriminations of better than one hertz near the middle of its range.

We shall return later to the problems of auditory processing and pattern recognition and to the way in which the brain deals with the mass of information provided by the ear. For the moment, we simply note that, while auditory information is largely temporal, it also has spatial components, and the recognition of these is aided in essentially all animals by the provision of two nearly independent auditory channels, each giving a slightly different auditory perspective as well as a vital backup system in case one of the ears is damaged.

SPATIAL PATTERNS AND VISION

Although the sense of hearing can give information about the direction from which sound comes, and indirectly about the location of structures emitting, reflecting or absorbing sound in our neighbourhood, the principal spatial sense is that of vision. Once again, we see an evolutionary pattern from simple light sensors that enable plants or primitive animals to seek or avoid the Sun's radiation, up to the highly specialised and efficient receptors in the higher animals and in man.

Nearly all natural electromagnetic radiation on the surface of the Earth comes from the Sun, so it is not surprising that visual organs have adapted to match it. The ozone in the atmosphere absorbs ultraviolet light, so most biological molecules that have evolved are unstable to ultraviolet radiation, a feature that has precluded visual sensitivity in the ultraviolet. Equally, the moderate temperature on the surface of the Earth, 300 K, has precluded the development of sensors, other than gross heat-energy detectors, in the infrared, though some cold-blooded animals have primitive infrared detectors which they can use, because of their lower body temperature, to detect warm-blooded prey.

The fundamental sensitivity limit of the eye in detecting an object like a star against an otherwise black background is set by the ratio of the nerve excitations produced by photons from the starlight to those produced by random thermal excitation of the dye molecules in the visual cells of the retina. In other situations, the detection limit is usually set by the level of stray light scattered from other bright objects in the field of view.

In either case, the fundamental relation (1) still applies, though it requires some re-interpretation. The bandwidth, for instance, is not the immense bandwidth of the optical part of the electromagnetic spectrum but rather, since the photoreceptors in the retina respond to the energy content of the photons in the light radiation and have a response time of about 50 milliseconds, a mere 20 hertz or so. On the other hand, the two-dimensional nature of the retina means that there are initially some 10^5 signal channels in parallel, with a consequent very large information rate.

Once again we shall postpone discussion of information rate and image processing to a later section, and content ourselves at this stage with the noting of a few more physical constraints upon the visual sense. The most important relates to spatial resolution, which depends on the wavelength of the radiation involved in the perception process. For sound, the wavelengths for human hearing range from about three centimetres to three metres, so that, even for high-pitched clicks, the ears are no more than about three wavelengths apart. This limits the resolution of sound direction to an accuracy of 10 degrees or so at best, even without the confusion caused by diffraction effects from nearby obstacles. In the case of visible light, the wavelength is rather less than one micrometre (1/1000 of a millimetre) and the pupil of the eye is several millimetres, or several thousand wavelengths across. This physical limitation would therefore allow a human eye to resolve two points or lines only one millimetre apart at a distance of about five metres. A person with good eyesight comes quite close to this limit, indicating that the density of receptor cells in the fovea, the area of most acute vision, is well matched to physical limitations.

The eye does not have this fine resolution over much of its visual field, for not only would this be wasteful of neural resources, but even counterproductive. It is extremely difficult to design a lens system with good resolution over more than the central part of its field of view, so a very fine-grained peripheral retina would be wasted, and there is considerable advantage to using larger, more sensitive and rather differently triggered receptors in the peripheral field of vision when the visual system is optimised to perform its many functions.

Like the auditory system, the visual system has a large and more or less logarithmic range of response between its detection limit and overload, in this case more than 70 decibels, or a factor of 10^7 in energy flux. The immediately available range is, however, a good deal less than this, and it takes several minutes for the eye to become adapted to large changes in light level.

CHEMICAL SENSES

Chemical perception was perhaps the earliest form to be developed by living organisms, for chemical signals determine at a primitive level the passage of nutrients and waste products through cell walls, and all neural processes are at root electrochemical. Clearly, since every organism is constantly bathed in chemicals, it is necessary that the chemical senses be very selective and able largely to ignore any sensations produced by common and necessary materials such as oxygen, nitrogen and water. The chemical receptors must therefore be specifically keyed to particular molecules or parts of molecules.

It is possible to imagine many ways in which this specificity might be achieved, but the most likely ones involve either membrane channels with size or electrical properties tailored to specific ions, or, in more complex cases, multiple adsorption sites upon the cell surface which activate a response only when they are all simultaneously stimulated by the presence of a particular matching molecule.

As with feature detectors in hearing or vision, so the extent to which an organism develops specific or generalised receptors may depend upon its evolutionary strategy. We might expect very simple animals, occupying a well-defined ecological niche, to have developed very sensitive and highly specialised receptors each of which triggers a specific response. This can be achieved only if a reasonably complex and unusual molecule is used as the messenger substance, for otherwise the noise produced by random chemical excitation of the receptor sites may trigger a false response. The pheromones that attract insects during mating behaviour are examples of such substances, but some insects, such as mosquitos, have specific receptors for molecules as simple as carbon dioxide, while even in humans the intense smell of hydrogen sulphide gas suggests the existence of a specific receptor.

Chemical receptor systems are capable of considerable elaboration through the incorporation of sets of cells responding to particular parts of complex molecules, so that the smell or taste of a substance is mapped onto a multidimensional sensory space. At a more primitive developmental stage, humans probably relied upon this ability in daily life, but the necessity has now faded. There is clear evidence, however, that such perceptual skills have not been entirely lost but can be developed by education and experience, as exemplified by winetasters, perfume blenders and skilled chefs.

MECHANORECEPTORS

For an organism to function it must be able to perceive its own state. This can be done to some extent by sight, but the basic information is that conveyed by sensors of strain, position and temperature located throughout and particularly on the surface of the body.

Temperature is readily transduced to nerve impulses, since the chemical activity of a cell is a strong function of temperature. Such temperature sensors are essential for maintaining a stable body temperature as well as for giving information about the environment.

The mechanical sensors are rather different from the others we have discussed, since they are often required to give information about static as well as dynamic situations, though both types are certainly present in the human body. Static strain sensors could depend on effects such as the variation of membrane permeability with elastic strain. Like most static sensors, they have evolved so as to fatigue rather rapidly, since the servo-systems that control the body rely largely upon information about changes in state, and a plethora of input signals transducing steady-state values would be redundant.

The mechanical receptors transducing changes in the relative positions of parts of the body, or shifting external stresses upon it, are similar in function to the hair cells that transduce the cochlear motions generated by sound. The differences are those of scale and mechanical force involved. The mechanoreceptors for touch and bodily motion are immensely large and robust compared with the cells in the cochlea (Figure 1).

INFORMATION RATE AND PATTERN RECOGNITION

Aural

When the signal power P in Equation (1) is very large compared with the random noise power N, then the limiting information transfer rate R_0 can become very large. This is often the case in real perceptual situations, for example when we are listening to a symphony concert or admiring a sunlit landscape. It is interesting to examine these two cases in some detail and to work out a few numbers in order-of-magnitude terms, just to see what the problems and possibilities are.

First consider the auditory case. The bandwidth W for human hearing ranges from about 100 hertz to rather more than 10 kilohertz, giving $W \sim 10^4$ Hz. In a concert hall, the background noise level is typically not much over 30 decibels relative to the standard sound pressure level at the limit of human hearing sensitivity for pure tones, and an orchestra

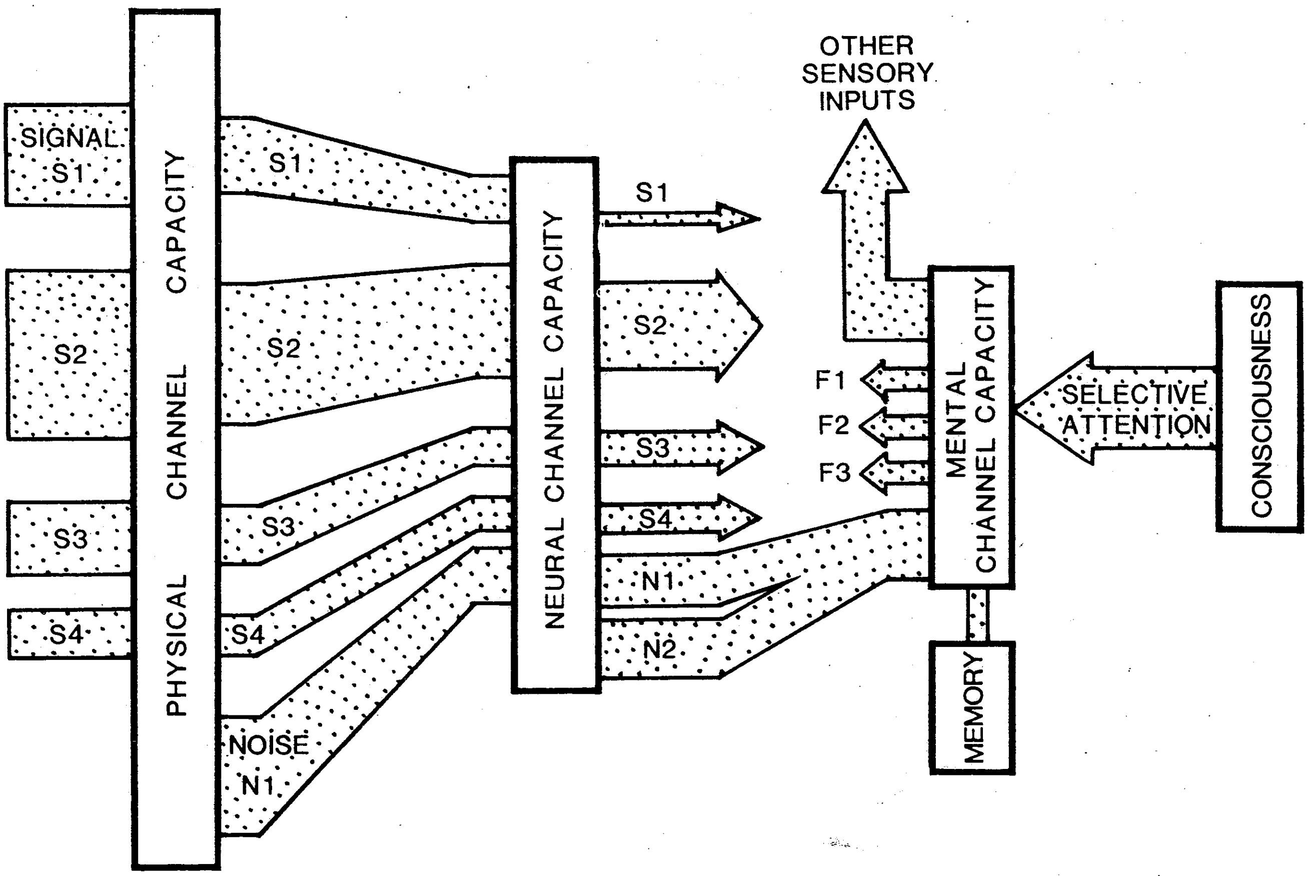

Figure 1. The physical signals S1, S2, . . . , some of which may be irrelevant and therefore regarded as interfering noise by the animal concerned, occupy only a small part of the information capacity of the physical signal channel. These signals are degraded by attenuation and by the addition of random noise N1 in the physical transmission process. The information capacity of the channel converting physical signals to neural signals is very much less than that of the physical channel, principally because of response-time limitations, and the conversion process adds further noise N2. The high-level mental channel has an even more restricted information capacity and must, in addition, process information from other sensory inputs. It is aided in this task by feature detectors F1, F2, . . . which may be fixed, as in simple animals, or partly adjustable on the basis of information stored in memory in the case of higher animals. The conscious mind has a still more limited information capacity, in a formal sense, and relies on selective attention to filter its sensory inputs further.

can easily produce a 90 dB average level with peaks over 110 dB, so that we can take the available signal-to-noise ratio P/N to be around 80 dB, or a factor of 10^8. Since $10^8 \sim 2^{26}$, the limiting aural channel capacity R_0 is, from Equation (1), about

$$R_0^{(A)} \sim 3 \times 10^5 \text{ bits per second.} \qquad (2)$$

How well does a real human auditory system perform in relation to this criterion? In simple terms, we can make an estimate as follows. The human ear divides up pure tone processing in the cochlea on a spatial basis so that tones well separated in frequency do not interfere too much with each other. The critical band within which tones mask each other significantly has a width of around one third of an octave, or about a ratio of 1.24 in frequency. There are thus about 30 of these 1/3-octave bands spanning the hearing bandwidth, and we can regard them as 30 nearly independent channels, essentially in parallel. Within one channel we can just notice a difference of about one decibel in sound level and, in a short time, about one per cent in frequency, giving about 80 loudness steps and 24 frequency steps or about 2000 distinguishable sensations within the critical band. Since $2000 \sim 2^{11}$, recognition of one of the points in this sensation grid gives us 11 bits of information. This is rather an overestimate for the lower end of the hearing range but the error is not significant for our present purpose.

Now the ear can resolve sensations occurring about 0.05 second apart, so that these 11 bits of information could be passed on 20 times a second, giving about 200 bits per second. Adding together the capacities of each of the 30 channels gives

$$R^{(A)} \sim 6000 \text{ bits per second.} \qquad (3)$$

This is a rate only about 2 per cent of the limiting rate $R_0^{(A)}$ given by (2), which is reassuring theoretically, but let us see what it implies.

The task of listening to an orchestra with the degree of attention specified above would be roughly equivalent to keeping track of 30 different instruments, all playing random notes as rapidly as possible – clearly not something that even the best musician could attempt. In terms of the information content of language – thinking technically of information now, divorced from meaning – this is also equivalent to recognising nonsense syllables spoken at the rate of more than 100 per second.

Obviously this is not what our brains do, even though the ear itself may be capable of providing information at this rate. A computer of very modest power could perform the task with ease, but instead our brains have evolved to abstract from this mass of sensory data just those items forming patterns in which we are interested.

We have already mentioned the trade-off that is possible, in both physical and perceptual terms, between time resolution and frequency resolution. This is partly an innate and partly a recently learned ability, for it is only with the development of rather sophisticated musical instruments that such frequency discrimination has assumed any particular importance, while time resolution is an integral feature of spatial location. Much more interesting is the pattern recognition mechanism which has evolved to process harmonically related complex sounds such as those produced by the human voice. It is not yet clear whether the processing is done in the time domain or the frequency domain or, as is most likely, in a combination of both. It does, however, enable the brain to perceive such a harmonically related sound as an entity having certain more abstract attributes, and to concentrate attention upon this entity to the virtual exclusion of extraneous noise or other similar sounds perceived as different entities. It is the existence of these mechanisms which allows the brain to deal so precisely with the harmonically related tones produced by musical instruments and with the harmonically related rhythmic structures we call music.

Visual

The ultimate channel capacity attainable in the visual region of the optical spectrum is immense if we have available fast-response narrow-band coherent generators and detectors such as lasers, dispersive spectrum analysers and photodetectors. The bandwidth is of the order 10^{17} Hz and a signal-to-noise ratio of 70 dB would allow an information rate of over 10^{19} bits per second for a single channel.

The biological visual system, however, does not operate in this way. Each receptor element responds to about one third of the visual range and has a response time of about 0.05 second. The signal-to-noise ratio in sunlight is perhaps 70 dB but there is an adaptation time lag before the extremes of this range can be used. Assuming 1 dB, or about a 25 per cent change in brightness, to be detectable, the information rate for a single visual channel is around

$$R_1^{(V)} \sim 100 \text{ bits per second.} \qquad (4)$$

Now, each eye has a spatial resolution of around one degree in the field of peripheral vision and perhaps 0.05 degree in the fovea, which has a field of diameter about one degree. Since the visual field of each eye is about 120°, there are a few times 10^4 picture cells altogether in the field, and this becomes about 10^5 parallel channels when allowance is made for three colours and two eyes. This takes no account, of course, of any interconnection between adjacent receptors that may, and in fact does, occur in the retina.

Combining this information with (4) gives a total capacity $R^{(V)}$ for the visual receptor channels of the order of 10^5 times $R_1^{(V)}$ so that

$$R^{(V)} \sim 10^7 \text{ bits per second.} \qquad (5)$$

This is something like 10 times the information rate for a colour television signal, which agrees with subjective impressions, since the imperfections in such a picture are clearly visible if one sits so that it fills one's field of view.

The potential rate $R^{(V)}$ available from the receptor cells in the eye is around 1000 times the auditory rate $R^{(A)}$ if we assume all the photoreceptor cells to be independent. The assimilation of even a minute fraction of this information by the human brain is impossible. Actually, of course, the rate at which information is presented to the visual system is itself severely limited – most aspects of a visual field remain constant for large lengths of time, and the eye is controlled mechanically to lock onto a significant feature of the image to minimise changes; detectors sensitive to stimulation change can therefore transmit the significant stimuli at a much smaller information rate.

On top of this strategy, the eye employs geometrical feature detectors of various types to search the image for significant visual structures, such as edges or corners, and it is information on these which is then fed on to the brain for further processing. Such two-dimensional pattern-recognition processors in the spatial visual field are analogous to the one-dimensional temporal pattern-recognition processors involved in hearing.

As with the ear, it may well be that early perceptual experiences help to determine or at least to reinforce the genetically determined features of this neural processing system. Certainly there is an immense array of problems associated with two-dimensional pattern perception and its implied three-dimensional configuration in real space that psychophysicists are only now beginning to understand. The multiple dimensionality of the visual perception problem makes it very much more complex than the time-series problem encountered in auditory perception.

CONCLUSION

This brief survey of some of the physical principles governing the processes of perception in general, and human perception in particular, has shown us that, once a working perceptual system has evolved – and the possibilities and limits here are fairly clearly understood – the major problem is that of handling the huge mass of sensory data that becomes available in normal good-signal situations. It is only for the very simplest of experimental situations that physical limitations such as signal-to-noise ratio become significant.

In the present context, this means that, while there are certainly physical problems concerned with perceptual mechanisms that remain to be solved, most of the important problems lie in less concrete domains of discourse. The road to understanding can be pursued in two directions. On the one hand we can start from physics, where we have begun, and follow the perceptual pathway through anatomy and neurophysiology into the depths of the brain. On the other, we can begin with the black-box approach to the whole problem of perception that is the beginning of empirical psychology and psychophysics, and then, through heuristic models and formal algorithms, try to devise plausible mechanisms by which the whole system might work.

Most times, the roads driven into the jungle of the mind from these two accessible encampments of understanding will fail to meet, but a little of each road will be useful for the next attempt, even if only by warning of impenetrable thickets, and perhaps one day the link will be complete. That day will not come soon, and indeed we have little idea even of the dimensions of the forests we are setting out to explore.

Acknowledgement

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